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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

Technical Progress Report

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Subject: Submittal of the Interim Progress Report, FR21998-22

Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney

Margaret B Hall
Margaret B. Hall
Contract Data Coordinator

cc: <u>With Enclosures</u>

Director, Naval Research, Code 2627
DPRO
Defense Technical Information Center (2 copies)
Dr. K. Sadananda

I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200+Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials is characterized by parallel continuous primary dendrites spanning the casting without interruption

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[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metal Park, Ohio, pp. 205-214

in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely non-crystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at no cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

We have repeatedly pointed out that global octahedral fracture plays a pivitol role in cataloging damage states in single crystal (SC) alloys. An understanding of the conditions under which this mode becomes operative and the effect it has on threshold and da/dN behavior is of critical importance to life prediction.

In previous monthly progress reports, we have described a hierarchy of microscopic fracture modes that exert a controlling influence on fatigue crack growth (FCG) behavior in PWA 1480 and PWA 1484. The effect these modes have on crack growth rate can be compared directly in constant cyclic stress intensity tests where some other parameter such as frequency or environment is varied to initiate a fracture mode transition. These fracture mode comparisons are facilitated by the fact that they can all be observed under Mode I loading conditions and analyzed with a Mode I stress intensity solution.

Global octahedral fracture can not be readily be compared to the others because it is driven by shear loading.

For global or monoplanar (111) fracture to occur in FCG testing a Mode II loading component is required. In Mode I testing unwanted (out of plane) crystallographic fracture frequently occurs on (111) planes that are not perpendicular to the direction of applied load. In this case, although octahedral fracture is produced, it can not be analyzed with a Mode I crack growth stress intensity solution. In tests where the (111) crystallographic plane is subjected to pure Mode I loading, fracture is non crystallographic, again preventing us from characterizing (111) fracture. This situation is described in Figure 1.

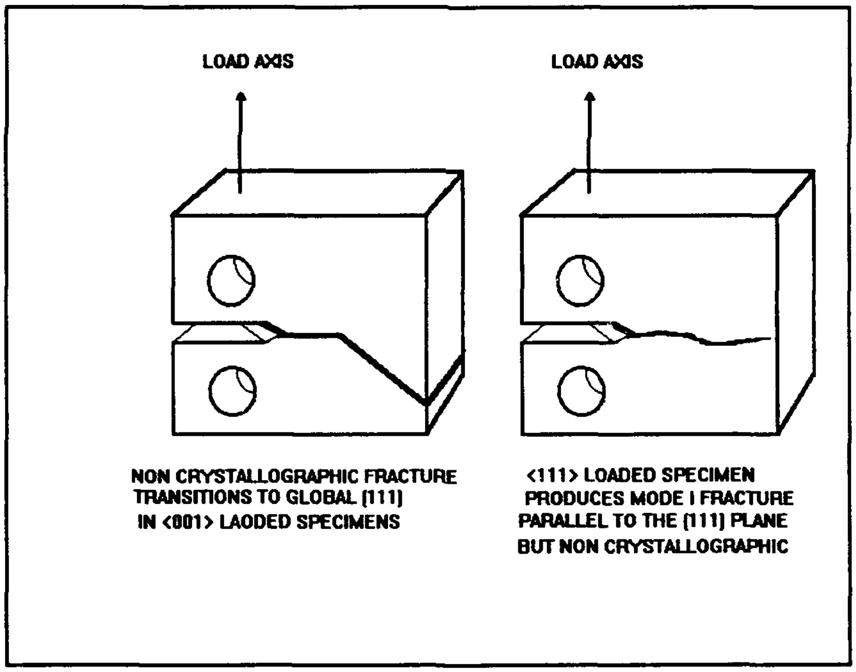


Figure 1. An out of plane crystallographic crack in a <001> loaded single crystal FCG specimen (Left). A <111> loaded specimen produces noncrystallographic fracture roughly parallel to (111) planes (Right).

Techniques for obtaining Mode II da/dN vs. ΔK data are available. Two methods are shown in figure 2. The beam specimen iis 4 point loaded to obtain shear at its center. In Figure 3 the "Brazilian Disk" specimen is compressivly loaded at its diameter. The angle of the starter notch with respect to the load direction is set to produce shear parallel to the preflaw.

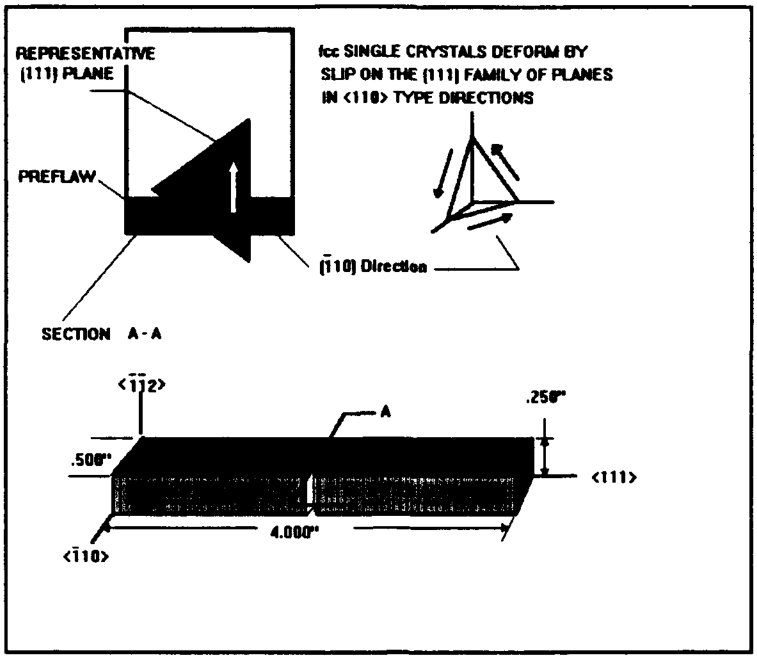


Figure 2. A schematic of a shear beam FCG specimen. In single crystal testing, the materials' preferred slip plane and direction are positioned coincident with the specimen shear plane.

In evaluating octahedral shear it is of critical importance that the material's shear plane, the (111) plane, be positioned (with extreme accuracy) coincident with the specimen's shear plane. In this way a comparison of crystallographic shear can be made with non crystallographic shear. Further, octahedral slip occurs on the (111) in specific directions (the <110> family of crystallographic directions). It may also be useful to study the effect of loading direction on crystallographic fracture by considering loading direction as a variable. This is shown schematically in Figures 4 and 5.

In work planned for the coming month we shall examine this fracture mode more closely.

IV. Current Problems

No technical problems have been encountered during the reporting period.

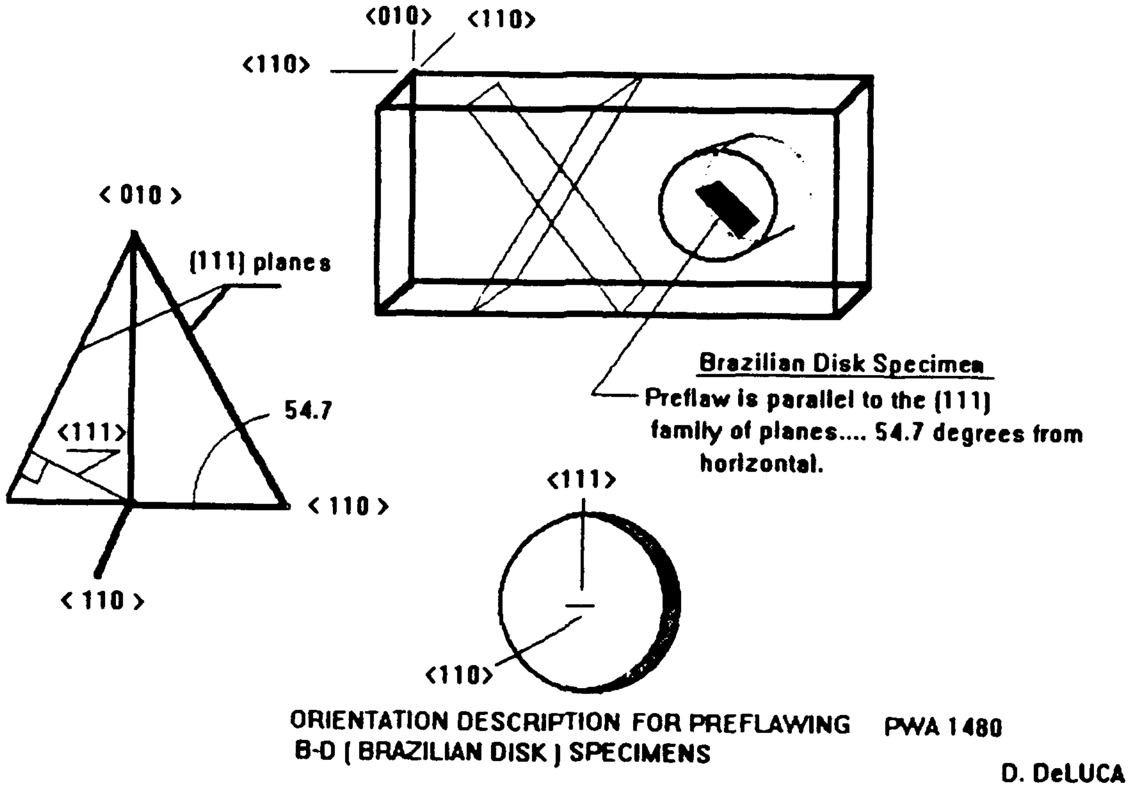
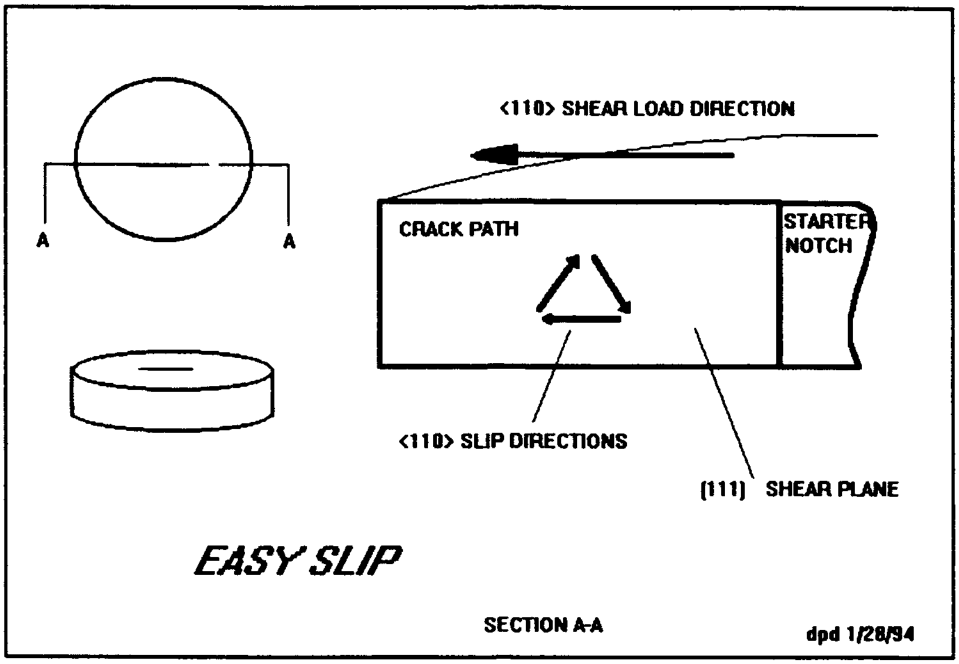


Figure 3. The Brazilian disk FCG specimen. The disk is loaded in compression at the diameter. The angle of the preflaw with the load axis determines the crack tip loading conditions. Obtaining properly oriented specimens is critical in evaluating (111) FCG data.



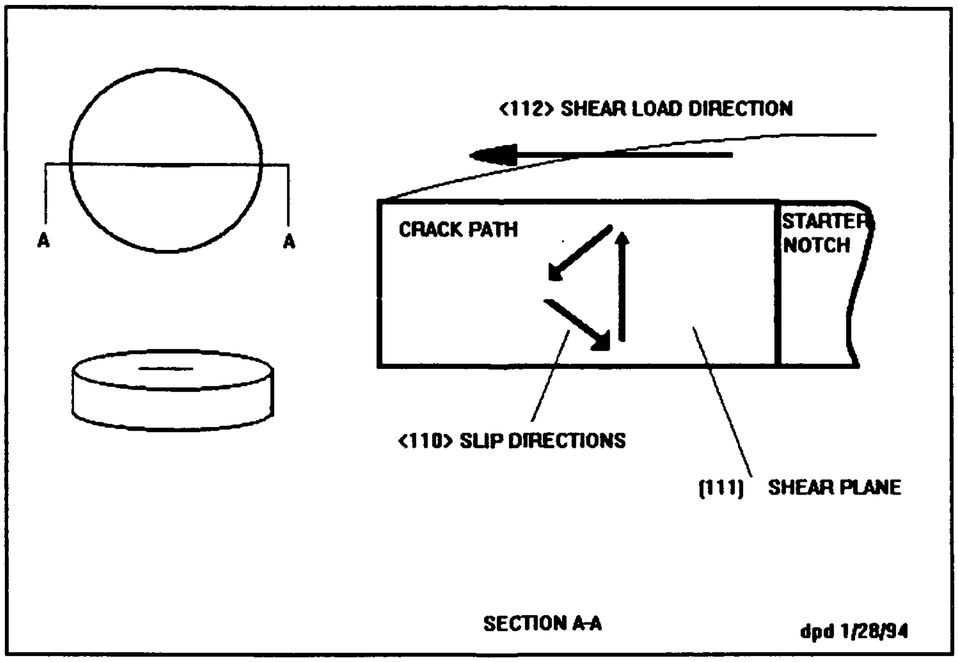


Figure 4. Schematics of Brazilian disk specimens with shear loading in the preferred slip direction (easy slip), at top, compared to shear loading oblique to the preferred slip direction, at bottom.

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16. Abstract (Limit: 200 words)

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.

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